Atmospheric Neutrinos: Past, Present and ...

John M. LoSecco
Physics Department, University of Notre Dame
Notre Dame, Indiana 46556-5670 USA
E-mail: losecco@nd.edu

This paper reviews the history of the atmospheric neutrino anomaly. The historical record does not support more recent claims that the anomaly constitutes evidence for a neutrino mass. Most experiments have reported an apparent muon deficiency which is independent of energy and distance. Time dependent variations in the Super Kamioka results are noted.

1 Prehistory

1.1 Opportunity

The early history of the atmospheric neutrino anomaly is closely tied to the growth of grand unified theories. Grand unified theories inspired the experimental search for proton decay which led to large well shielded detectors. The primary background to proton decay was due to atmospheric neutrinos so they were studied in some detail. Neutrino oscillations figured prominently at the first workshop on grand unification. About half of the IMB paper at that meeting [1] was devoted to the question of studying neutrino oscillations with atmospheric neutrinos.

1.2 Early Indications

Early indications that atmospheric neutrinos were not behaving as expected came because many interesting proton decay modes produced unstable particles such as kaons and muons that could be expected to decay in the detector and yield a delayed coincidence with the primary event. In looking for these delayed coincidences it was noticed that there appeared to be too few of them in the global data sample. Based on 148 events Shumard reported [2] that 26$\pm$4% of the observed events had a muon decay. Careful studies had indicated that a decay rate of 35$\pm$1% was expected. This 2.1 sigma difference was discounted in the thesis.

Confirmation came from the Kamioka experiment in Japan. Kajita's thesis [3] had evidence for a 2.4 sigma deficit of muon decays based on 89 single ring events, But no note of the deficit was made in the thesis.

The atmospheric neutrino statistics rapidly increased and the deficit was noted in a 1986 IMB publication [4]. A 3.3 sigma difference was reported based

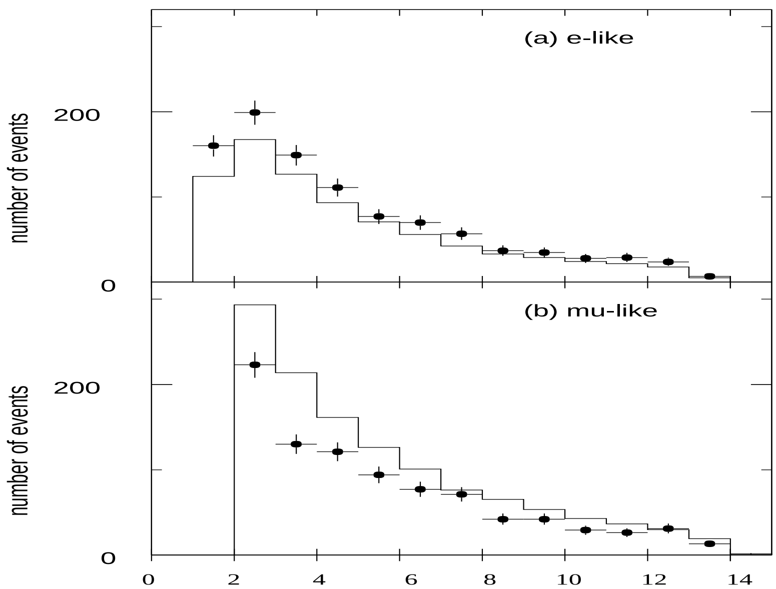

Figure 1: The electron and muon neutrino spectra as reported by the Super Kamioka experiment

on 401 events. 26±2% of the events contained a muon decay when 34±1% was expected.

1.3 Flux Modeling

In all of these cases there were suspicions about the *expected* values. The atmospheric neutrino flux, the neutrino interaction model and the detector response were all required for an estimate. Substantial effort went into modeling the neutrino interactions themselves. (This is because the high multiplicity neutrino interactions were the most serious background to the proton decay signal). Shumard had used Freon bubble chamber data as a model of neutrino interactions. Kajita and Haines had used neutrino interaction models which they compared with deuterium bubble chamber data.

Except for the muon decay rate deficiency the observations were all in good agreement with expectations of atmospheric neutrinos. The rate of interactions, their homogeneity in the detector and the *isotropy* of the signal were as expected [5,6].

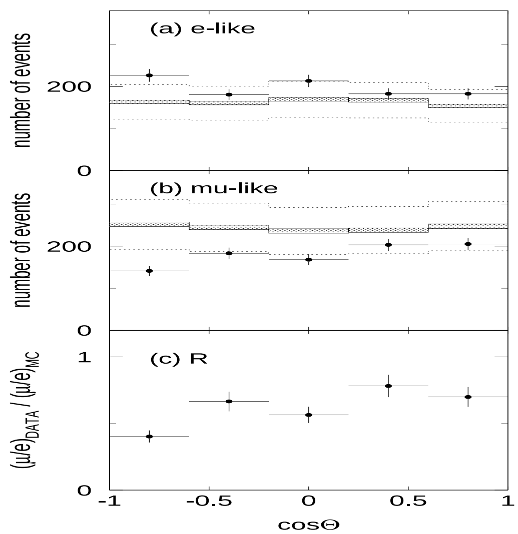

Figure 2: The electron and muon neutrino zenith angle distribution as reported by the Super Kamioka experiment. The bottom plot is the zenith angle distribution for R.

2 The Classical Period

2.1 Rapid Progress

The Kamioka group applied a *revised* form of their particle identification methods to follow up on these indications to establish the general properties of the anomaly [7]. The early work implied that the effect could be due to either a deficit of muon neutrinos or an excess of electron neutrinos. Uncertainties in the flux normalization did not permit one to discriminate between these two possibilities. To reduce the dependence on the absolute flux normalization the Kamioka group introduced a variable called R, $R = (\frac{\mu}{e})_{Obs}/(\frac{\mu}{e})_{Expect}$, which was only sensitive to the relative normalization of the muon and electron neutrino flux.

Typical of the results from this period is an apparent energy independent excess of electron type events and an apparent energy independent deficit of muon type events. This is illustrated in figure 1 which is taken from the Super Kamioka early work [8]. The solid curve is the expected value the points are the data. This confirms prior work [7,9,10] on these properties. These data have $R = 0.61 \pm 0.03(stat.) \pm 0.05(sys.)$ which is well below the expected value of

1. This value of R seems to be energy independent [8] over the range of energies illustrated.

The angular distribution of the effect is very important in testing neutrino evolution effects. Atmospheric neutrinos from above have traveled a few 10's of km. Those from below have traveled on the order of 10,000 km. R as a function of zenith angle from early Super Kamioka work [8] illustrates the most important features of the angular distribution.

While IMB [9] and Kamioka [7,10] have shown purely isotropic distributions the most important feature is still present in figure 2, the Super Kamioka plot. Note that the electrons are high and the muons are low at all angles. The value of R is significantly low over all of the solid angle, even at 0°. This implies that even atmospheric neutrinos with short path lengths, on the order of 10's of kilometers, are effected by the anomaly.

2.2 Uniformity in Energy and Direction

The isotropic angular distribution could be misleading. The direction reconstructed and plotted is the charged lepton direction emerging from the neutrino interaction. This has a reasonable correlation with the incident neutrino direction, but it is not exact [1]. Two factors mitigate the significance of this scattering effect. The directional correlation improves with energy and the distance scales very slowly with angle except near the horizon. The majority of the atmospheric neutrino events from above have traveled on the order of 10's of km. Those from below have traveled the order of 10,000 km. So scattering within the hemisphere has only a small effect on the distance traveled. With regard to the first factor, the data indicates [11] that the isotropy for both the electron and muon samples is still present at higher energies. See figure 4.

Since neutrino oscillations were always a potential hypothesis for such an effect and since there was no apparent energy or distance dependence in the contained neutrino events another source of signal could be used to extend the sensitivity or corroborate the oscillation hypothesis. Figure 3 shows the exclusion plot for the $\nu_\mu \rightarrow \nu_\tau$ hypothesis using upward going neutrinos [12] and the ratio of stopping to through-going upward muons [13]. The Frejus limits [14] are also shown. Most large mixing angle Δm^2 were ruled out by the combination of analyses reviewed in this paper [13]

2.3 Consistency

By early 1998 the anomaly had been consistently observed in about 8 independent measurements. All the observations were consistent with an R value of 0.61.

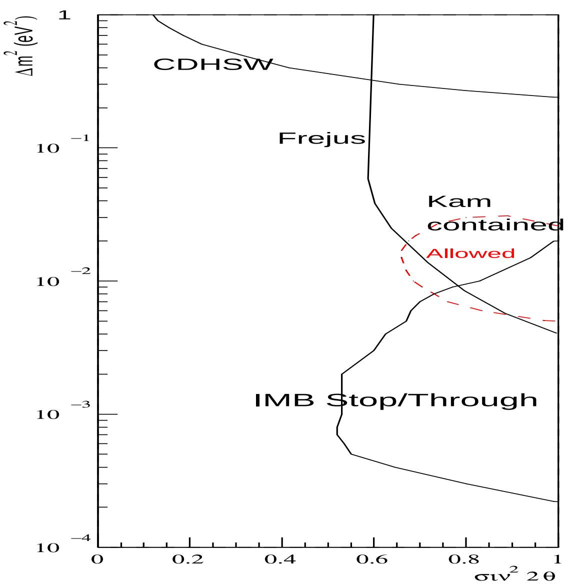

Figure 3: The exclusion plot for $\nu_\mu \rightarrow \nu_\tau$ from a number of experiments. The IMB Stop/Through excludes the region favored by recent Super Kamioka analyses and much of the region permitted by the older Kamioka analysis too.

Experiment	Measured R value
Kamiokande Sub-GeV	0.60±0.07±0.05
Kamiokande Multi-GeV	0.57±0.08±0.07
IMB	0.54±0.05±0.12
Frejus	1.00±0.15±0.08
Nusex	0.99±0.29
Soudan	0.64±0.17±0.09
Super Kamiokande Sub-GeV	0.61±0.03±0.05
Super Kamiokande Multi-GeV	0.66±0.06±0.08

2.4 Up/Down Energy Independence

The atmospheric neutrino flux is not truly isotropic. The Earth's magnetic field, which varies from point to point limits the flux of primary cosmic rays which can get close enough to the atmosphere to interact. Fortunately at some sites, such as the IMB site, the effect is small. IMB was located at 81.27° west and 41.72° north where the the downward flux was expected to be about 5%

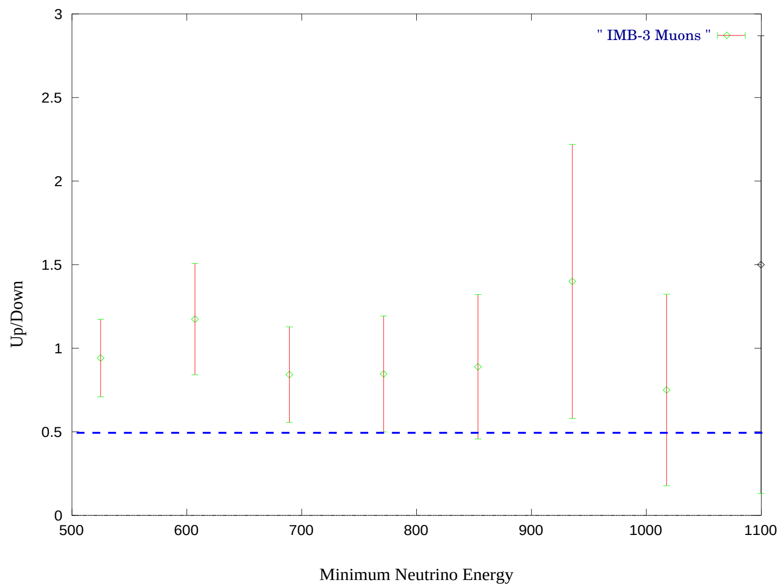

Figure 4: The upward over downward muon rate in IMB3 plotted as a function of the minimum energy. There is no indication of an asymmetry at any energy.

greater than that coming from below. The geomagnetic effects decrease with energy (but are replaced by path length effects at high energy.) In setting limits at IMB it has been customary to neglect the small geomagnetic effects. Any reduction in the upward flux due to geomagnetic effects would be attributed to the phenomena in question. This neglect of geomagnetic effects at IMB makes the limits obtained slightly conservative. In other words in setting limits for neutrino oscillations a larger region could have been excluded if geomagnetic effects were taken into account.

Limits based on the up/down rate for muon neutrino interactions in IMB-3 [9] are shown in figure 5. The up over down ratio is shown as a function of the minimum neutrino energy in figure 4. While the statistical errors grow with energy as fewer events are used, the data are consistent with an energy independent value of 1. There is no evidence for an up-down asymmetry in this data.

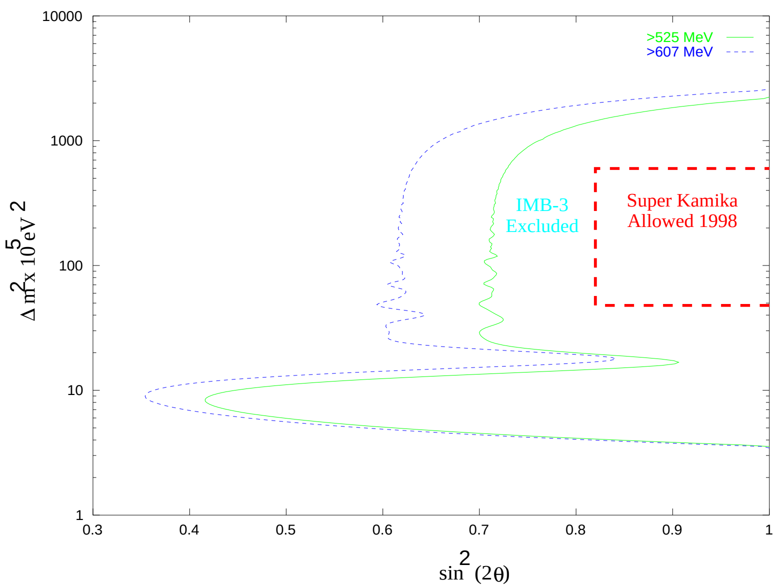

Figure 5: The excluded region extracted from the IMB3 upward over downward muon rate. The region favored by the Super Kamioka experiment is ruled out by this measurement and the one illustrated in figure 3. The larger excluded region uses all of the muon neutrino events. The smaller region uses those events above about 600 MeV.

3 The Modern Era

The hint of a directional modulation, present in figure 2 apparently evolved and in mid 1998 the Super Kamioka collaboration published [15] it as evidence to support the neutrino oscillation hypothesis (figure 6). This result has been widely discussed and interpreted. It is noteworthy that the mass fit to the Super Kamioka data was barely consistent with the earlier Kamioka neutrino analysis. The reason for this difference is that the two data samples are indeed different. Earlier experiments, including Kamioka do not corroborate the Super Kamioka observations of anisotropy. The anomaly is still manifest at 0° in this data [15]. It can not be accommodated by the Δm^2 of the fit but is handled by several other fit parameters. Both the μ to e flux ratio and the up to down flux ratio are fit as part of the oscillation analysis.

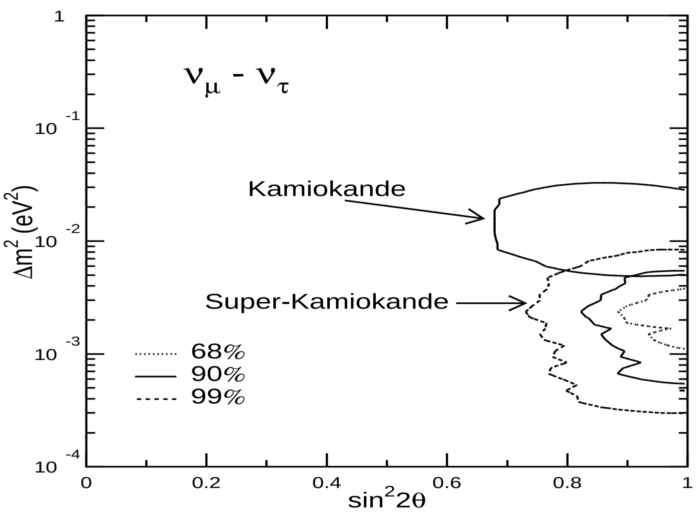

Figure 6: The Super Kamiokande and Kamiokande allowed regions for $\nu_\mu \to \nu_\tau$ oscillations.

4 The Post Modern Era

The modern period did not last long. In January 1999 the Super Kamioka group presented [16] additional data to increase the exposure from 414.4 days to 736 days. The data was presented in a manner to bolster confidence in the neutrino oscillation hypothesis. But under closer examination [17] the additional data appeared to be *inconsistent* with the sample that had already been published.

Without detailed access to the data it is hard to understand the exact nature of the change. Manifestations of the problem are a 12±3% drop in overall event rate for the sub-GeV event sample. Most of the drop seems to be due to a 18±5% drop in the "electron neutrino" interaction rate and a 20±5% drop in the multi-ring rate. The muons manifest a not significant 3±5% rise. There is no significant change in the multi-GeV data sample.

Since the observed "electron neutrino" rate has dropped there is a significant change in R over values reported earlier. The value of R reported in the new sub-GeV sample was, $0.76 \pm 0.04(stat.) \pm 0.06(sys.)$. The earlier value was $R = 0.61 \pm 0.03(stat.) \pm 0.05(sys.)$. Only the statistical error is relevant in comparing these two numbers since they are taken from the same experi-

ment and share the same systematic error. To the extent that the atmospheric anomaly is $R \neq 1$ this variation is rather shocking.

5 What Next?

The apparent temporal variation may be a significant factor in understanding what is actually happening with the anomaly. We have been assured that the temporal effect is not a result of systematic error. If it were attributable to systematic error it would invalidate much of the Super Kamioka physics but not help in furthering our understanding of the effect. The Super Kamioka group has shown evidence [18] of the stability of their detector. Previous experiments such as Kamioka [11] and IMB have found no indications of temporal variation. There is some evidence [17] that the change in R is continuing and has not yet reestablished a constant value.

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